A Search for the Higgs Boson in its Associated Production with a W boson at the Fermilab DØ Experiment

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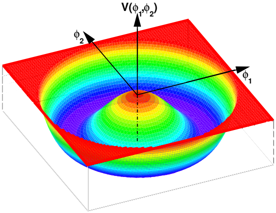
Outline

- Introduction and Motivation
- Experimental Apparatus
- Higgs Searches at Tevatron
- Run II A Dataset
- Background Modeling
- Object ID Efficiencies
- High Level Analysis
- Tagging *b*-quark Jets
- Optimization
- Systematic Uncertainties
- Cross Section Limits
- Summary and Conclusions

Electroweak Symmetry Breaking/Higgs Mechanism

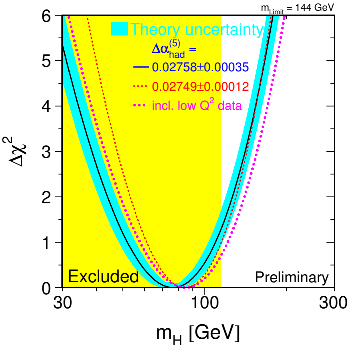
- $SU(2)_L \otimes U(1)_Y$ gauge theory is tested to a great precision. It is not an exact symmetry of our vacuum. Otherwise, quarks, leptons and gauge bosons would all be massless!
- Simplest solution: Complex doublet of scalar fields, *i.e.*, 4 degrees of freedom (4 dof) in a ϕ^4 potential: $V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$, $\mu^2 < 0$, $\lambda > 0$

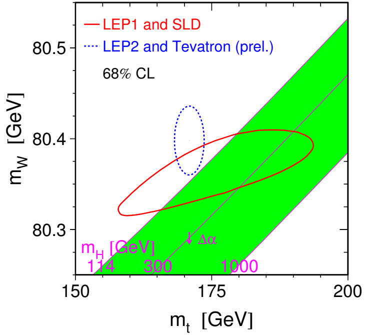


- $\langle\Phi\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$ where $v = \sqrt{-\mu^2/\lambda} \neq 0$
- Non-zero VEV $\langle\Phi\rangle_0$ spontaneously breaks the global symmetry

- $\mathcal{L}_{Higgs} = \left|(\partial_\mu + igW_\mu^\alpha T^\alpha + ig' B_\mu)\Phi\right|^2 - V(\Phi)$
- Transverse polarizations of $W^\pm$ and Z absorb 3 out of 4 dof. Remaining one is the fundamental scalar H

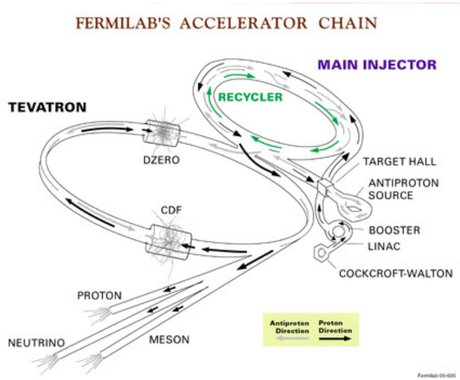
Experimental Constraints on the Higgs Mass





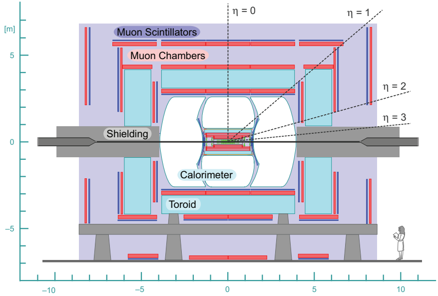
- Precision fits to electroweak data with M_{top}=170.9 $\pm$ 1.8 GeV
- Direct search at LEP excludes $M_H \leqslant$ 114.4 GeV@ 95% CL
- M_W=80.413 $\pm$ 0.048 GeV(CDF) $\Rightarrow$ Data prefers lighter Higgs!
- Best fit of $M_H = 76^{+33}_{-24}$, or $M_H <$ 144 GeV

Tevatron Synchrotron



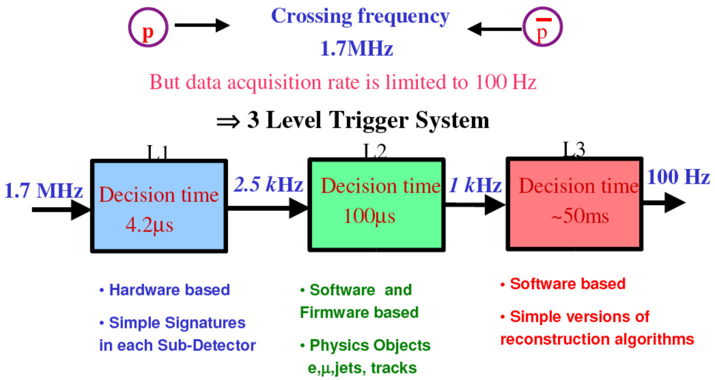
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- 1000 superconducing magnets, 4 mi. circumference, $W^{\pm}/Z$ factory
- Bunch crossing every 396 ns.
- Run IIA: April 2002 - April 2006
  $\sim$1.3 fb^{-1} delivered

Upgraded DØ Detector



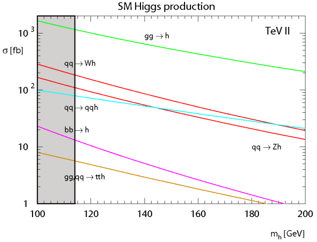
- CC:$|\eta| < 1.1$; EC: $1.5 < |\eta| < 3.0$
- DAQ and CAL electronics upgrades
- Triggers on tracks and displaced vertices
- Run IIA: $\sim$1.0 fb^{-1} recorded

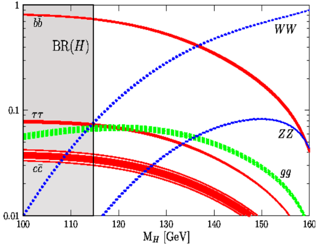
DØ Triggering System

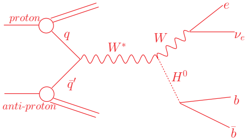


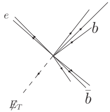
- Triggers for a specific physics group: B Physics, Electroweak, Higgs, QCD, Top
- Objects: e/γ, μ, τ, jets, $\not\!\!E_T$ and combinations of these
- For "rare"/unknown phenomena: Maximize exposure rate ⇔ minimize prescale for highest luminosities

Higgs - Production and Decay at the Tevatron



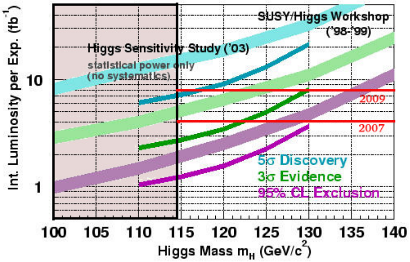






- Gluon fusion dominates $\sigma(gg \to H) = 0.8$ - 0.2 pb
- $\sigma(\mathrm{WH}) = 0.2$ - 0.03 pb
- WH is accessible and easy to trigger
- $M_H < 135\ \mathrm{GeV}: H \to b\bar{b}$
- Two b quarks $\Rightarrow$ b-tagging
- $W \to e\nu \Rightarrow$ lepton and $\not{E}_T$
- $M_H > 135\ \mathrm{GeV}: H \to WW^*$

Higgs Search Sensitivity



1. $p\bar{p} \rightarrow WH \rightarrow \ell\,\nu\, b\bar{b}$
   $(\ell = e, \mu, \tau \rightarrow e/\mu)$
2. $p\bar{p} \rightarrow ZH \rightarrow \ell\,\ell\, b\bar{b} \quad (\ell = e, \mu, \nu)$
3. $p\bar{p} \rightarrow WH \rightarrow W\,W^{+}\,W^{-}$
4. $p\bar{p} \rightarrow H \rightarrow W^{+}\,W^{-}$

- DØ Collaboration published *WH* results in electron channel with 174 pb^{-1}
- Combined results from electron and muon channels 400 pb^{-1} are currently in review for publication in PLB
- Analysis results presented here correspond to 1.04 fb^{-1}
- Increase in detector acceptance, Optimization of *b*-tagging, and "OR"ing Triggers are new to this analysis

Dataset, Triggers and Luminosity

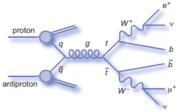
- Initial Dataset: ∼**335 million events** on tape
- Data Quality: Compromised data flagged by each subdetector (∼5%)
- Subskim: ∼**590 thousand events** remain when requiring at least
  - one good, track-matched EM object, $p_T > 15$ GeV
  - two good jets corrected for their energy scale, each with $p_T > 15$ GeV
- **EM+Jet** Triggers: Integrated Luminosity of **1.04 fb^{-1}**

List	Trigger	pb^{-1}
v8	EM15_2JT15	23.35
v9	EM15_2JT15	24.73
v10	EM15_2JT15	9.81
v11	EM15_2JT15	63.40
v12	E1_SHT15_2J20	227.35
v13a	E1_SHT15_2J_J25	55.22
v13b	E1_SHT15_2J_J30	298.21
v14	E1_SHT15_2J_J25	333.57
		Total 1035.64

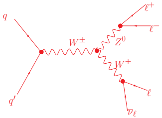
- Single-EM Triggers (Calorimeter-based, Track-based, "OR"-combination)
- An OR-combination of all Single-EM and EM+Jet

Physics Background

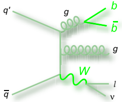
- $t\bar{t} \rightarrow \ell\ell\nu\nu b\bar{b}$



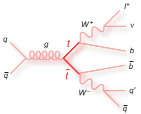
- $WZ \rightarrow jj\ell\ell\ell\nu$



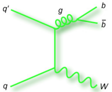
- $Wjj \rightarrow \ell\nu jj$



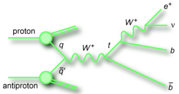
- $t\bar{t} \rightarrow \ell\ell jjb\bar{b}$



- $Wb\bar{b} \rightarrow \ell\nu b\bar{b}$



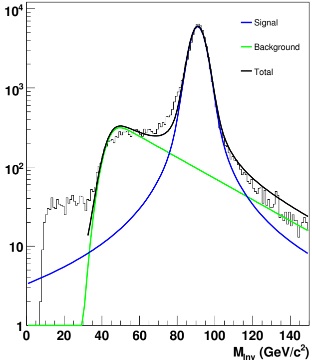
- $tb \rightarrow \ell\nu b\bar{b}$



- Physics background processes are simulated using `PYTHIA`, `ALPGEN` and `COMPHEP`
- All events undergo full DØ detector simulation
- All bakgrounds are normalized to their SM cross sections except $W + jets$
- $W + jets$ is normalized to data after subtracting all other backgrounds from it.
- $W + jets$ is largest in pre-tagged and $t\bar{t}$, Diboson and tb are significant in b-tagged events

Tag and Probe Method

$Z \rightarrow e^+e^-$ Invariant Mass Spectrum



- Two EM candidates with M_{Inv/e^+e^-} consistent with a Z boson
- Tag must pass stringent cuts
- Probe is required to pass the cuts relevant to the efficiency being determined, *i.e.*, trigger
- Fit signal/background using Voigtian/falling-exponential
- Probe EM object is matched to L1/L2/L3 objects ($\Delta R < 0.4$)
- If there is a match at all three levels, probe passes trigger
- Trigger Efficiency, $Eff_{trig}(\eta, p_T)$

$$= \frac{\#\text{Probe objects passing trigger}}{\#\text{Probe candidates}}$$

Combining Triggers: “OR”ing Pedagogy

E1_SHT25 $\longrightarrow$
- L1 CEM(1, 12)
- L2 L2EM(1, 15)
- L3 ELE_NLV_SHT, 25

- L1: Cal. EM object, $E_T > 12$ GeV
- L2: L2 EM cluster with $E_T > 15$ GeV
- L3: Requires an electron satisfying tight shower shape requirements with $E_T > 25$ GeV

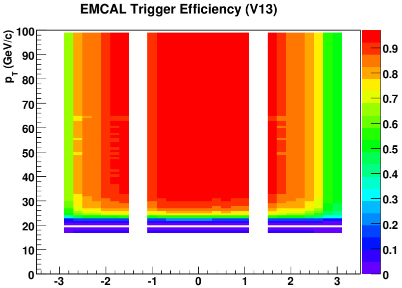
EM_MX	EM_HI	EM_MX_SH	EM_HI_SH
EM_MX_EMFR8	EM_HI_EMFR8		
E1_SHT20	E1_SH30	E2_SHT20	E2_SH30
E3_SHT20	E3_SH30	E1_L50	E1_VL70
E1_SHT22	E1_SH30	E2_SHT22	E2_SH30
E3_SHT22	E3_SH30	E4_SHT22	E4_SH30
E1_L70	E1_NC90	...	...

Name	L1	L2	L3
EM_A	$L1_A$	$L2_A$	$L3_A$
EM_B	$L1_B$	-	$L3_B$
EM_C	$L1_C$	$L2_C$	$L3_C$

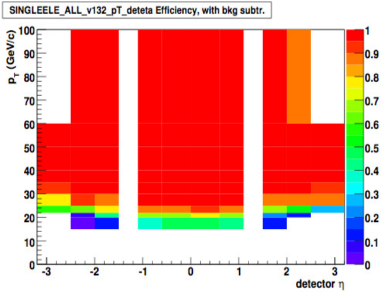
- PassProbe(EM_A \|\| EM_B \|\| EM_C) $\equiv$
  MatchProbe($L1_A$ \|\| $L1_B$ \|\| $L1_C$) &&
  MatchProbe($L2_A$ \|\| $L2_C$) &&
  MatchProbe($L3_A$ \|\| $L3_B$ \|\| $L3_C$)
- The luminosity of the dataset is determined for the unprescaled trigger

Trigger Efficiency: Single-EM "OR"

Eff_{trig} Calo-only *vs.* p_T, η_{det}



Eff_{trig} Calo+Trk based *vs.* p_T, η_{det}



- Calo+Trk based triggers have higher efficiency compared to Calo-only
- Especially true for $p_T^e < 20$ GeV for $|\eta_{det}| < 1.1$
- Enables to lower p_T threshold for selection of electrons
- Marginal improvement in efficiency for $1.1 < |\eta_{det}| < 2.5$
- To apply trigger efficiency to MC event, $Eff_{trig}(p_T^e, \eta_{det}^e)$ is applied as an event-weight

Trigger Efficiency for Simulated Events

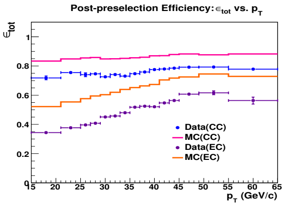
$$\mathtt{EM15\_2JT15} \longrightarrow \begin{cases} \mathtt{L1} & \mathtt{CEM}(1,10)\ \mathtt{CJT}(2,5) \\ \mathtt{L2} & \mathtt{EM}(.85,10.)\ \mathtt{2JET}(10.) \\ \mathtt{L3} & \mathtt{Ele}(\mathtt{ELE\_LOOSE\_SH\_T},1,15.)\ \mathtt{Jet}(\mathtt{SCJET\_9},2,15.) \end{cases}$$

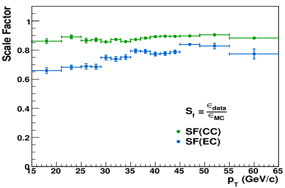
- Trigger Efficiency for each level/each object is determined separately
- To apply the overall trigger efficiency per event for MC, define
  P(L1 L2 L3) = P(L1) × P(L2|L1) × P(L3|L2 L1)
- Triggering on electron is independent of trigger on other objects *i.e.*, jets, $\not{E}_T$
  P(e,jet) = P(e) × P(jet)
- Overall event-wide probability of passing EM+Jet Trigger is given by
  P(L1 L2 L3, e, jet) = P(L1,e) × P(L2|L1,e) × P(L3|L2 L1,e) ×
  P(L1,jet) × P(L2|L1,jet) × P(L3|L2 L1,jet)
- Luminosity weighted Probability

$$\mathrm{P(evt)} = \frac{\sum_{ver} \mathcal{L}_{ver} \cdot P_{ver}(evt)}{\sum_{ver} \mathcal{L}_{ver}}$$

Object ID Efficiency

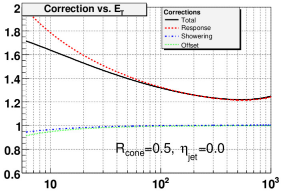
☞ Electron

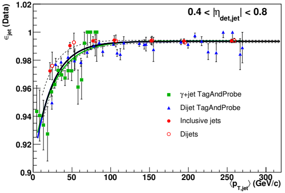




ϵ_{ID} (%)	CC	EC
Data	77.6 ± 0.3	63.3 ± 0.4
MC	86.6 ± 0.1	70.6 ± 0.2

☞ Jets





- $f_{JES} = \frac{E^{corr}_{jet}}{E^{uncorr}_{jet}} = \frac{1}{E^{uncorr}_{jet}} \cdot \frac{E^{uncorr}_{jet} - O}{F_\eta \cdot R \cdot S}$
- JES Correction: (30-45)% $\pm$ (3-5)%

W + 2(or 3) Jets: Event Selection Criteria

☞ Electron

- $f_{EM} > 90\%$, $f_{iso} < 15\%$
- Shower shape: $\chi^2_{HMx7} < 50$
- Track match to EM cluster (E/p + spatial)

	p_T	Acceptance
CC	>15 GeV	$\lvert\eta\rvert < 1.1$
EC	>25 GeV	$1.1 < \lvert\eta\rvert < 3.0$

- EM Likelihood: $>$ 85% (Tight), $>$ 20% (Loose)

☞ Missing E$_T$ ($\not\!\!E_T$)

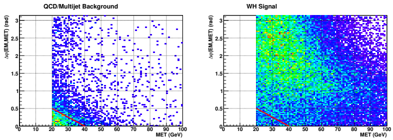
- CC: $\not\!\!E_T$ > 20 GeV
  EC: $\not\!\!E_T$ > 25 GeV

☞ Two/Three Jets

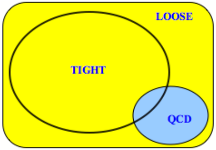
- Jet energy scale corrected, good (L1conf) Jets
- Jet_1 $p_T > 25$ GeV
  $Jet_{2,3}$ $p_T > 20$ GeV
- $\lvert\eta\rvert < 2.5$, n90 > 1
- $0.05 < f_{EM} < 0.95$, $f_{CH} < 0.4$

☞ Other

- No other isolated electron or muon in the event
- $\Delta\phi(\not\!\!E_T, e) > 1 - 0.25 \times \not\!\!E_T$



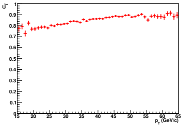
QCD/Multijet Background

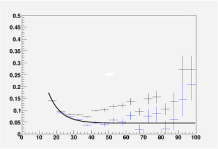


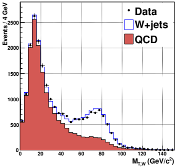
Trigger List	Fake Rate 2 jets (%) CC	Fake Rate 2 jets (%) EC	Fake Rate 3 jets (%) CC	Fake Rate 3 jets (%) EC
v8-11	5.4 ± 0.2	6.3 ± 0.2	6.0 ± 0.2	7.7 ± 0.2
v12	5.7 ± 0.1	8.2 ± 0.1	8.4 ± 1.0	8.3 ± 0.3
v13	6.0 ± 0.1	8.5 ± 0.1	8.2 ± 1.0	10.3 ± 1.0
v14	6.6 ± 0.1	8.8 ± 0.1	6.6 ± 1.0	8.8 ± 1.0

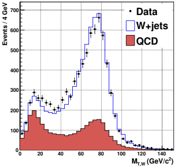
1. $N_{loose} = N_{em} + N_{qcd}$
2. $N_{tight} = \epsilon_{lh} N_{em} + \epsilon_{qcd} N_{qcd}$

- ϵ_{lh} isdeterimed using tag and probe method
- ϵ_{qcd}: $\not\!\!E_T < 10$ GeV
  One good jet $|\eta| < 1.1$, $f_{EM} < 0.7$



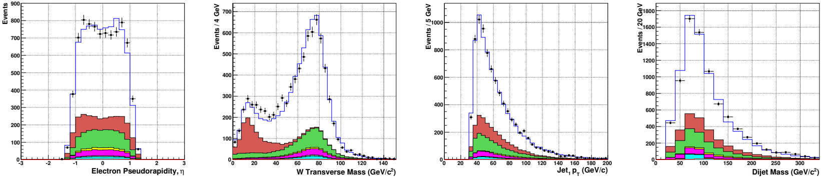




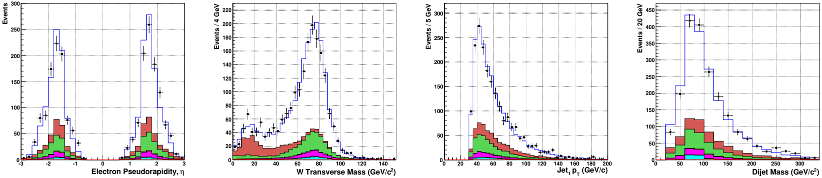


Evidence for W + 2 Jets Production

CC Analysis



EC Analysis

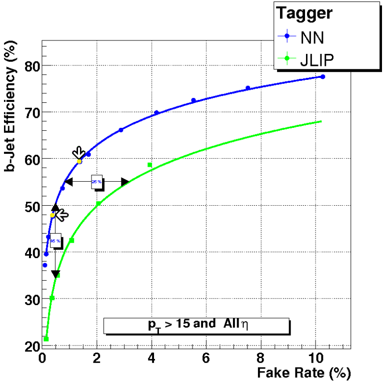


- data W+jets QCD $Wcc/W\tau\nu$ $t\bar{t}$ $Wb\bar{b}$ tb WZ WH

Identifying *b*-quark jets: *b*-tagging

Neural Network Tagger - Seven Inputs

1) Decay length significance of the displaced vertex
2) Impact parameter significance of tracks
3) Probability that the jet originates from the primary vertex
4) χ^2/N_{dof} of the fit to the displaced vertex
5) No. of tracks used for displaced vertex
6) Mass of the tracks used for the displaced vertex
7) No. of displaced vertices found in the input jets

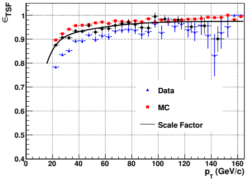


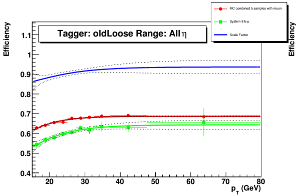
- NN tagger: Large improvement compared to individual taggers
- Taggability: Jet has at least two tracks each with $p_T > 1$ GeV
- Double Tag (DT) Loose operating point
- Exclusive Single Tag (EST) Tight operating point

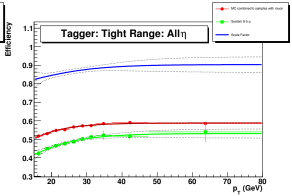
Tag	Effy. (%)	Fakerate (%)
DT	59.3	1.7
EST	47.6	0.55

Tagging Jets in Simulated Events

- Tag Rate Functions (TRF): Probability of NN-tagger to tag a *b*-quark, *c*-quark, light-quark jets
- Data and MC have differences in tracking related quantities
- Two different approaches
  - Tag MC jets. Correct for difference in taggability and tagging efficiency $W^{MC}(jet) = \epsilon^{MC}_{taggability} \times SF_{taggability} \times \epsilon^{MC} \times SF_{b\rightarrow\mu}$
  - Compute event-wide probability, P(jet) $= \epsilon_{taggability} \times$ TRF(jet)



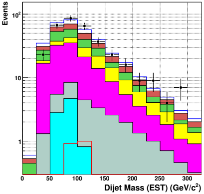




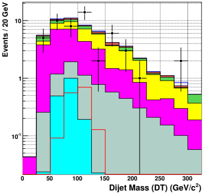
Dijet Invariant Mass in *b*-tagged Events

W + 2 Jets (CC/EC) | **W + 3 Jets (CC)**

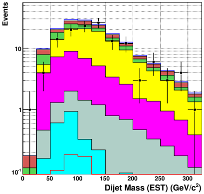
362.2±48.0/354/1.26



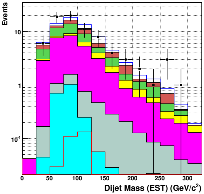
57.1±8.6/51/0.74



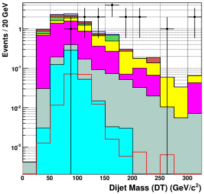
169.1±23.2/136/0.31



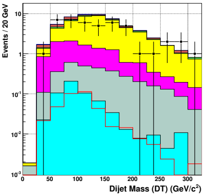
71.3±10.3/78/0.16



9.5±1.4/16/0.10



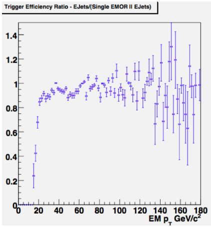
57.8±11.0/46/0.2

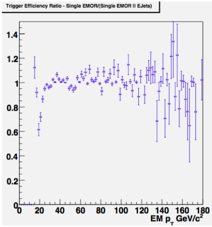


● data ❑ *W*+jets ■ QCD ■ *Wcc*/*Wτν* ■ $t\bar{t}$ ■ $Wb\bar{b}$ ■ *tb* ■ *WZ* ❑ *WH*

Trigger Optimization

- Overall combination has higher efficiency than Single-EM alone or EM+Jets alone
- Define the probability of an event to pass Single-EM or EM+Jet Triggers
  P(Single-EM || EM+Jet) = P(e of EM+Jet) × P(jet of EM+Jet) + P(Single-EM)
  - P(e of EJets && Single-EM) × P(jets of EM+Jet)





☞ Signal Significance: (systematics not quoted)

	Single-EM		EM+Jet		Combined	
	ST	DT	ST	DT	ST	DT
WH Signal	1.08	1.04	1.77	1.04	1.60	1.48
Expected MC	523.0	177.6	634.3	132.5	796.9	249.9
Observed Data	495	178	596	115	835	279
$S/\sqrt{B}$	0.048	0.089	0.070	0.090	0.057	0.094

Systematic Uncertainties

Total Uncertainty: $\sim$ 12% for WH and WZ, $\approx$ 26% for Wjj and $Wb\bar{b}$, $\sim$ 19% for $t\bar{t}$, tb and QCD

- **Electron:**
  - Reconstruction and identification: 3%
  - Trigger efficiency: 3%
  - Calibration of the electron energy: 3%
  - Electron energy smearing: 3%
- **Primary vertex reconstruction:** 4%
- **Jets:**
  - Jet Energy Scale: $\approx$ 2%
  - Reconstruction and identification: 3%
  - Jet multiplicity/fragmentation: 5%
- ***b*-tagging:** Wjj $\approx$ 21.2% and $\sim$12% for the rest
  - Taggability
  - Tagging scale factor for NN
- **Luminosity:** 6.1%
- **Theoretical cross section:** $t\bar{t} = 16\%$, $tb = 18\%$, $Wjj \approx 20\%$, 6-9% rest of the processes

The CL_s Statistical Approach

- Choose dijet invariant mass as the final variable
- Define two hypotheses

  Background Only (Null) Hypothesis, H_0 $\equiv$ No signal

  Signal+Background Hypothesis, H_1 $\equiv$ Presence of WH signal
- Define a Poisson **L**og **L**ikelihood **R**atio (LLR) test statistic

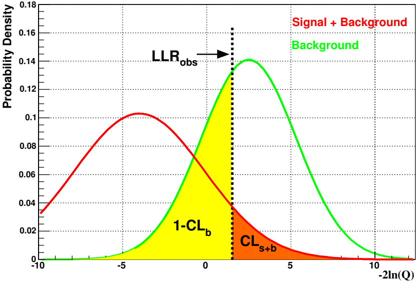
$$Q(\vec{s}, \vec{b}, \vec{d}) = \frac{P(data|H_1)}{P(data|H_0)} = \frac{e^{-(s+b)}(s+b)^d}{d!} \Big/ \frac{e^{-b}(b)^d}{d!}$$

$$\chi = -2\ln Q = 2\left[s - n\ln\left(1 + \frac{s}{b}\right)\right]$$

- Define a confidence level for B-only and S+B hypotheses

$$CL_n = \int_{\chi_{obs}}^{\infty} \frac{dP_n}{d\chi} d\chi \qquad n = b, s+b \tag{1}$$

CL_s Illustrated



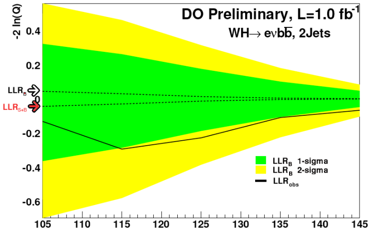
- PDF for B-only and S+B are populated via outcomes of repeated trials
- Green curve is the Poisson PDF $dP_b/d\chi$ with mean value b
- Red curve is the Poisson PDF $dP_{s+b}/d\chi$ with mean value $s+b$
- Black dotted line is the observed LLR, χ_d
- By construction $CL_s = CL_{s+b}/CL_b$
- S+B hypothesis is excluded at 95% CL when 1 - CL_s ≤ 0.95

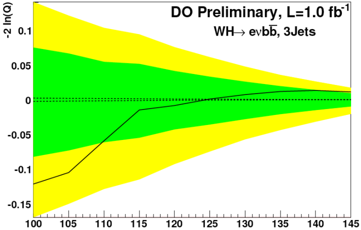
Effect of Systematics

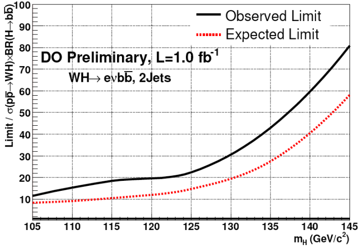
- Systematics are included into the signal and background outcomes of MC trials via Gaussian distribution
- Total uncertainty is 10-20% for signal and 10-25% for backgrounds
- Theoretical cross section, *b*-tagging, Luminosity, Jet Energy Scale, Lepton ID
- Expected Limit: Assumes hypothetical outcome matching expected background

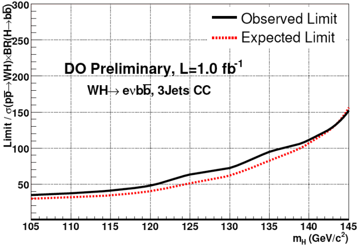
- LLR_b - LLR_{s+b} Separation indicates discrimination power of analysis
- 1σ and 2σ width of LLR_b indicates sensitivity of analysis to signal-like fluctuation in data
- $LLR_{obs} < 0 \Rightarrow$ data is signal-like. Observed limit $>$ Expected Limit
- $LLR_{obs} > 0 \Rightarrow$ data is background-like. Observed limit $<$ Expected Limit

Limit Ratio and Analysis Sensitivity

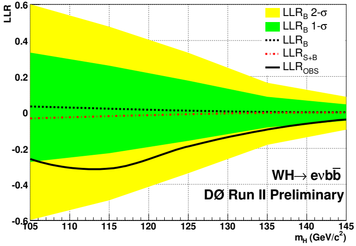


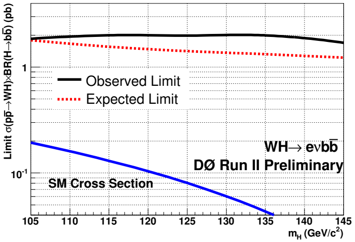






Cross Section Limit for $W(H) \rightarrow e\nu(b\bar{b})$





☞ $m_H = 115\ \mathrm{GeV}/c^2$ Limit Ratio ($\sigma_{SM} = 0.13$ pb)

Analysis	σ_{exp}/σ_{SM}	σ_{obs}/σ_{SM}
Moriond CC (2jet)	12.6	16.8
CC (2jet)	10.5	18.4
CC (2jet & 3jet)	10.1	20.7
CC+EC (2jet)	10.1	15.1
CC+EC (2jet & 3jet)	9.9	18.4

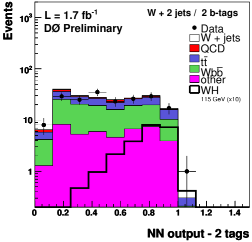
Summary

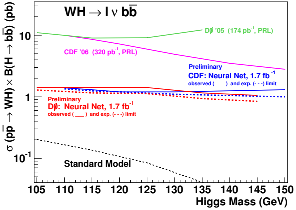
- W + 2jets, W + 3jets (control sample) events are analyzed in EST and DT tagged events
- Significant improvement in sensitivity is achieved compared to previous analyses in addition to an increase due to higher luminosity
  - NN-tagging: $\sim$35% per jet $\Rightarrow$ 1.35 $\times$ 1.35
  - Include End Calorimeter: $\sim$20% $\Rightarrow$ 1.2 (VSK)
  - "OR"ing of Triggers: $\sim$15% $\Rightarrow$ 1.15 (VSK)
  - b-tag working point optimization based on $S/\sqrt{B}$ (VSK/Yuji)
- Overall increase in sensitivity: **factor of 1.6** from electron channel

- No signal is observed in excess of the SM prediction.
- 95% CL upper limits are derived on the production cross section $\sigma(p\bar{p} \rightarrow WH) \times BR(H \rightarrow b\bar{b})$ as a function of Higgs mass in the range $105 < m_H < 145$ GeV$/c^2$.

Conclusions

- $WH \rightarrow \ell\nu b\bar{b}$ $\ell = e\,\mu$ combination yields factor of 2.1 increase in sensitivity
- 0.67 fb^{-1} of additional data included in the combination. Does not include EC analysis or Trigger optimization





- Further improvements in analysis (NN selection, Improving mass resolution of dijets, electron/muon ID)
- Plans for publication of combined result in PLB foreseen in the near future
- Prospects to exclude low mass Higgs at Tevatron are bright with DØ and CDF results combination by 2009

Systematic Uncertainties

Source	WH	WZ	$Wb\bar{b}$	Wjj	$t\bar{t}$	tb	QCD
Trigger eff.	3.0	3.0	3.0	3.0	3.0	3.0	
Primary Vertex Reco.	4.0	4.0	4.0	4.0	4.0	4.0	
EM ID/Reco eff.	3.0	3.0	3.0	3.0	3.0	3.0	
EM Likelihood eff.	3.0	3.0	3.0	3.0	3.0	3.0	
EM energy/smearing	3.0	3.0	3.0	3.0	3.0	3.0	
Jet ID/Reco eff.	3.0	3.0	3.0	3.0	3.0	3.0	
Jet multiplicity/frag.	5.0	5.0	5.0	5.0	5.0	5.0	
Jet Energy Scale	2.0	2.0	3.0	2.0	3.0	1.0	
Jet taggability	3.0	3.0	3.0	3.0	3.0	3.0	
NN-tagger Scale Factor	2.0	2.0	2.0	15.0	2.0	2.0	
Acceptance err.	10.1	10.1	10.4	18.0	10.4	10.0	
Cross Section	6.0	6.0	9.0	9.0	16.0	16.0	
Heavy-Flavor K-factor			20.0	20.0			
Total uncertainty	11.8	11.8	24.3	28.4	19.1	18.9	18.8

Combined Limits: Full SM Combination